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DC Conduction and Discharge Activity in Hydrocarbon Oils Subjected to Reduced Pressure

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ABSTRACT. The effect of reduced pressure on the DC quasi-steady state and discharge activity in hydrocarbon oils has been studied experimentally. Non-uniform high DC field is applied to fresh and aged transformer oil and liquid paraffin sample. The applied pressure is reduced from about 133 to 6.6 kPa and then increased vice versa for each applied voltage inside a controlled vacuum chamber.

At a fixed voltage level the quasi steady state current is found to remain almost unchanged with pressure reduction down to a certain critical sub-atmospheric pressure, where after the current behavior is different for different oils. It increases or decreases sharply for transformer oil and liquid paraffin respectively. The value of this critical pressure increases as the applied voltage is increased. Reduction of pressure has similar effects on discharge activity as well. The experimental results suggest that vaporization and molecular structure of oils play an important role at sub-atmospheric pressure.

Little is known about the understanding of the effect of reduced pressure below atmospheric level on the DC conduction currents in hydrocarbon oils. Most investigators studied the vacuum breakdown between electrodes without introduction of liquid insulants (Tsuruta 1983, Fursey 1985). Whereas other investigators studied the impact of high pressure on the conduction current in liquids (Kao and Calderwood 1965, Hirano 1984). Presently, there is a need for systematic experimental investigation of the effects of space like environment of reduced pressure on the liquid insulants. As many of these materials may behave differently in vacuous environment than at atmospheric or high pressure.

In this report non-uniform high DC field is applied to transformer and paraffin oil samples. Experimental results of the effect of reduced pressure (below 133 kPa) on the quasi-steady state and discharge activities in oil samples at various applied voltages are presented and discussed.

Experimental Circumstances

In this study, three types of hydrocarbon oils were investigated: (1 & 2) Fresh and aged transformer oil samples conforming to the BS 148: 1972, which had density as 0.86×10^3 kg/m^3, viscosity as 6.88×10^{-3} to 9.89×10^{-3} Pa s at 300 K for fresh and aged oil respectively. Earlier investigations into these transformer oil samples by the spectroscopic analysis (El-Sulaiman *et al.* 1986) showed the presence of open chain aliphatic, alicyclic and aromatic hydrocarbons and the absence of carbonyl and polar groups. Their percentage compositions were 7-8%, 28-29% and about 64% for aromatics, napthenes, and paraffins respectively. (3) Liquid paraffin sample which was of laboratory heavy grade having a density 0.85×10^3 kg/m^3 and viscosity 54.4×10^{-3} Pa.s at 300 K. It was a normal straight-chained structured hydrocarbon (C_nH_{2n+2}).

Aged transformer oil sample used in this study was acquired from an Extra High Voltage (EHV) breathing transformer which had been operating without fault for the last seven years. All of the investigated samples were dehydrated and filtered at room temperature by using the technique described earlier (El-Sulaiman *et al* 1981). Non-uniform field was employed using point-plane electrodes which consisted of a steel needle of 50 μm radius and a brass plane electrode of 25 mm diameter with its edges rounded. Positive DC voltage was applied to the point electrode using a stabilized and regulated power supply. Gap spacing of 0.75 mm was maintained throughout this work and, conduction currents and discharge activity were measured at room temperature across a 10 kΩ resistor which was connected to a high sensitivity chart recorder as shown in (Fig. 1). The time constant of the measuring circuit was approximately 50 μs. The recorder traces detected as voltage signal were converted and were calibrated into nano-amperes by taking into account the input impedance of the recorder. The test cell was placed inside a stainless steel vacuum chamber of 0.2 m^3 capacity. Pressure could be reduced below atmospheric level with the help of a vacuum pump and a regulating valve down to 0.133×10^{-4} kPa. Currents were recorded with reducing pressure below atmospheric and then repeated with increasing pressure back to atmospheric. After each new setting, an average equilibrium time of not less than 120 seconds were elapsed before a new recording was started. Prior to each measurement, the test cell was conditioned by short circuiting and grounding the electrodes for about 60 seconds.

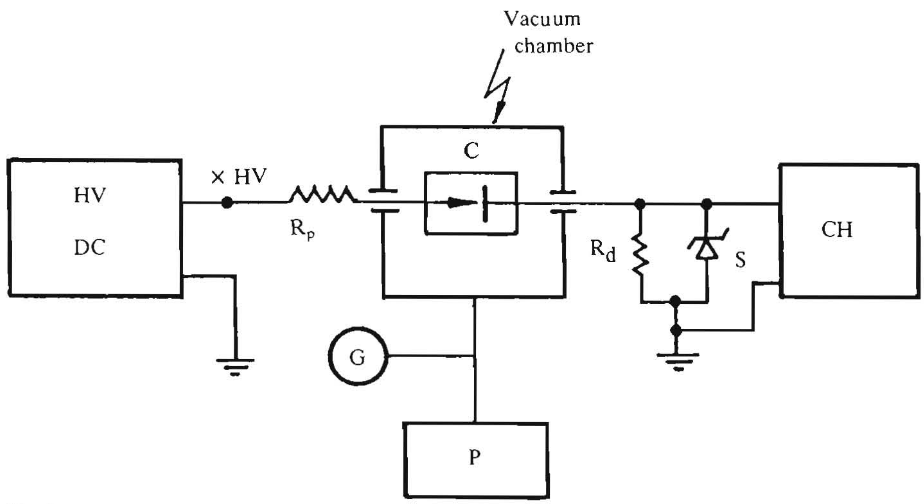

Fig. 1

Results and Discussions

Effect of Reduced Pressure on DC Conduction Current

Figs. (2a&b) show the dependance of quasi-steady state current (I_q) on sub-atmospheric pressure (P), at different applied voltages, for fresh and aged oils respectively. Each measured point on the figure represents an average of three experimental runs. The standard deviation was small within experimental error and is therefore not shown. Generally, it can be stated that the quasi-steady state current remains almost unchanged and independent on sub-atmospheric pressure to a certain critical low pressure (P_c). Whereafter the current tends to increase sharply towards breakdown. The values of this critical pressure is less than 40 kPa and decreases as applied voltage is decreased. For example, for fresh oil, the values of (P_c) are about 40, 26 and 6.5 kPa for applied voltages of 7, 5, and 4 kV respectively. Similar values of (P_c) are found for aged oil except it is about 13 kPa at 4 kV. No hysteresis is observed when the pressure varies in both directions (reducing or increasing). The sharp increase of the current behavior at critical pressure for different voltages has been fitted, using least square method, to different possible models. From the highest correlation coefficient results, it is found that the sharp increase in I_q with decreasing pressure P obeys an exponential form as:

$$I_q \propto \exp(Pc/P) \qquad (1)$$

where P = applied sub-atmospheric pressure,

P_c = critical sub-atmospheric pressure, and $P \leqslant P_c$

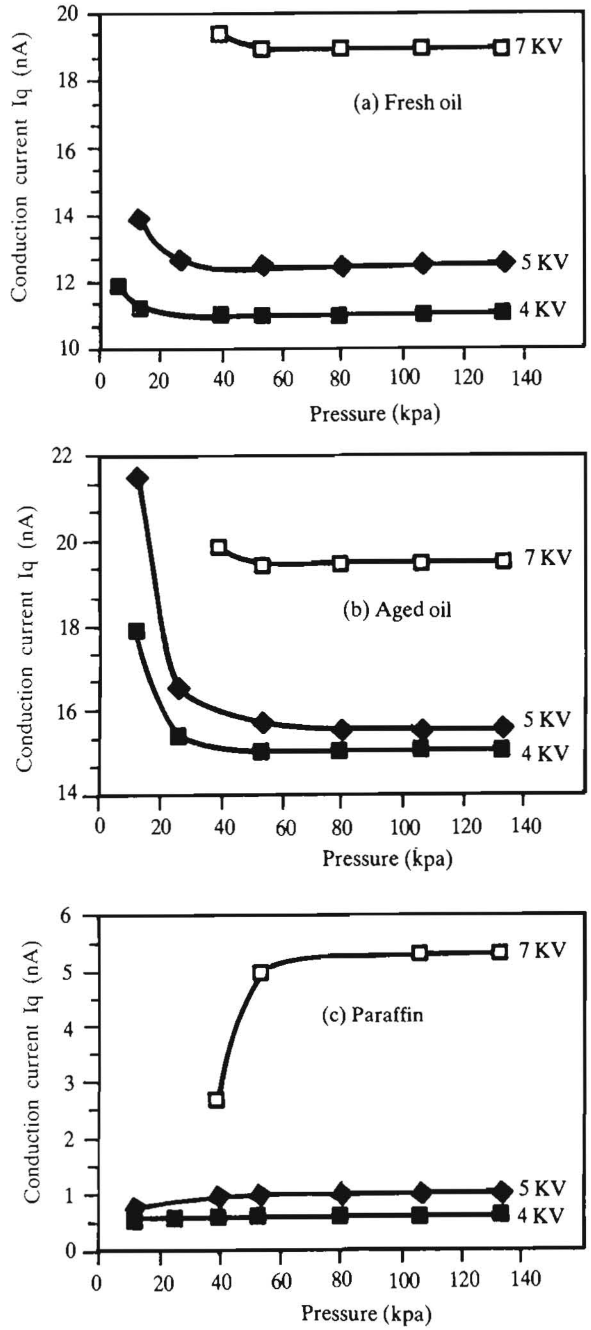
Conduction current Iq (nA)
20
18
16
14
12
10
0
20
40
60
80
100
120
140
Pressure (kpa)
7 KV
5 KV
4 KV
(a) Fresh oil
Conduction current Iq (nA)
22
20
18
16
14
0
20
40
60
80
100
120
140
Pressure (kpa)
7 KV
5 KV
4 KV
(b) Aged oil
Conduction current Iq (nA)
6
5
4
3
2
1
0
0
20
40
60
80
100
120
140
Pressure (kpa)
7 KV
5 KV
4 KV
(c) Paraffin

Fig. 2.

For positive point electrode, at normal atmospheric pressure and temperature, field emission occurs directly from oil molecules (Schmidt 1984) and is the dominant factor (El-Sulaiman 1991). With the reduction of pressure the energy deposited in the oil by current injection is enhanced, thus causing rapid increase in localized temperature. This in turn will lead to local vaporization (Kelly *et al.* 1989) and hence to current and discharge increase in the vapor cavities. However, the conduction current in Fig. (2a & b) shows independence down to about 40 kPa, which means that the vapor cavities were not yet grown enough. So it is more likely that the growth of vapor cavities increases at the critical sub-atmospheric pressure and is responsible for this current and discharge increase. As the pressure is decreased, then at higher values of applied voltage the number of injected charge carriers increases rapidly. Consequently the number of the vapor cavities grows reaching a large value at a relatively higher critical sub-atmospheric pressure than at lower applied voltage, thus resulting in an increase in conduction current. This sudden and large increment of conduction current will possibly lead to ensuing of breakdown, which is also aided by a simultaneous enhancement of discharge activity as shown in the next section.

It is found by comparing the performance of fresh oil and aged oil that the sample of aged oil exhibits larger conduction current than the sample of fresh transformer oil at applied voltage range of $4 \sim 5$ kV · This may be attributed to the presence of impurity charge carriers in the aged oil such as ferric iron (El-Sulaiman *et al.* 1986) which could enhance the conduction current. However, when the applied voltage is increased to about 7 kV, the conduction currents in both oils are almost the same. With the increase in voltage electrohydro-dynamic (EHD) instability at the vapor/liquid interface sets in and the impurity particles are expelled out of the interelectrode gap. This will result in nearly similar amplitude of conduction current in both oils. At this stage the conduction current is mainly governed by field emission from oil molecules.

Fig. (2c) shows the effect of reducing the pressure (P) on the conduction current (I_q) for paraffin oil. The phenomenon in the paraffin oil is opposite to that in transformer oil at low pressure. Although the DC conduction (I_q) is independent of (P) down to a certain critical low pressure (P_c) as in transformer oil, yet the current tends to decrease thereafter. The value of this critical pressure is generally less than 53 kPa, and decreases as the applied voltage decreases and is opposite to the case in transformer oil. The sharp decrease of current (I_q) with the decrease of pressure (P) in paraffin oil can be reprensented by:

$$I_q \propto [1 - \exp(Pc/P)] \qquad P \leqslant Pc \qquad (2)$$

The decrease of Iq with decrease in P becomes more prominent as the applied voltage increases. Similar findings have been reported earlier by Kao and Rashwan (1974) for technical grade benzene, where the electroluminescence intensity and breakdown are reported to increase with increasing pressure, while the phenomena is opposite for spectroscopic cyclohexane. They attributed this observation to the relation of the efficiency of current transport by either hopping or tunneling with the applied pressure. In the present case, it is likely that the solubility of oxygen in paraffin oil is relatively lower than in transformer oil and the removal of dissolved moisture and gas is more rapid. Moreover, the paraffin oil is a simple saturated normal straight-chained hydrocarbon with neither fractions nor additives. On the other hand, about one third of the transformer oil is napthenic, and saturated with cyclic hydrocarbons having closed ring structure. Aged oil samples investigated have been in contact with atmospheric oxygen in service, therefore the presence of oxidation products is inevitable. Certain light fractions are also part of the structure of transformer oil which play an important role on the effect of degassing process during pressure reduction. This is supported by the fact that the saturated vapor pressure of such an oil increases with the increase of light fraction percentage present in its bulk (Golovan *et al.* 1978).

Effect of Sub-Atmospheric Pressure on Discharge Activity

Table (1) shows the variation of the repetition rate of discharge activity with the reduction of pressure at applied voltages of 4, 5 and 7 kV. Generally the discharge repetition rate shows an unstable behavior with the decrease in pressure down to 53 kPa. But this activity suddenly becomes vigorous below 53 kPa. For example, Fig. (3) shows the chart recorder discharge activity traces, emphasizing the effect of reducing the pressure on discharge activity for paraffin at 4 kV. Above 40kPa, no discharge activity was observed. For transformer oil, below this critical pressure, the burst activity increases suddenly, with a simultaneous sharp increase in conduction current. For liquid paraffin, the behavior is opposite, i.e. the increase in discharge activity is accompanied by a decrease in conduction current. It has been shown in insulating oils that the discharge current burst activity and breakdown are associated with the discharge in the low density region in the liquid (Kelly *et al.* 1989).

These low density regions are high pressure vapor cavities. Lonization of these vapor cavities will depend on the hydrostatic pressure and voltage (Zaky and Hawley 1973). It has recently been reported (Denat *et al.* 1988) that the discharge activity repetition rate in transformer oil depends on the flow of interelectrode average conduction current and increases linearly with the increase in this current level. According to well known Claussius-Clapeyran (Reid *et al.* 1987) relation; the boiling point of the liquids decreases with the decrease in atmospheric pressure. Therefore the present experimental evidence that the critical low pressure increases with the increase in applied voltage, supports the vaporization hypothesis and confirms that discharge activity is related to pressure and average quasi-steady conduction current level.

Table (1) also summarizes the behavior of discharge activity in paraffin oil when subjected to reduced pressure levels. Generally the discharge activity is almost negligible down to 53 kPa. However, when the pressure is further reduced, vigorous discharge activity takes place as shown in Fig. (3). This onset of vigorous discharge

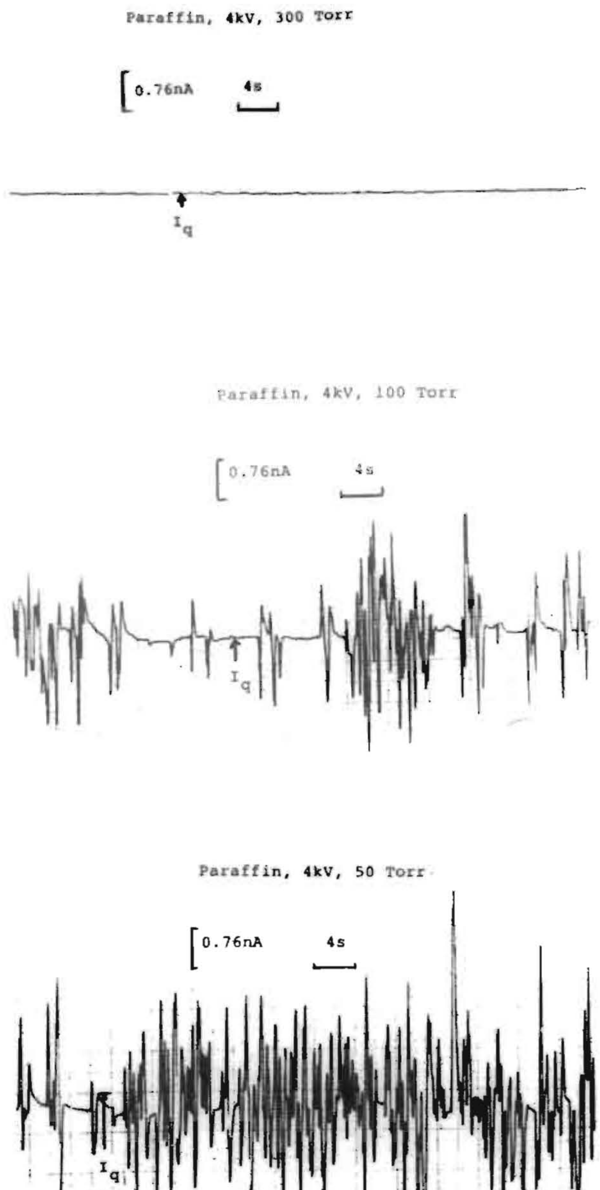
Paraffin, 4kV, 300 Torr
0.76nA
4s
I_q
Paraffin, 4kV, 100 Torr
0.76nA
4s
I_q
Paraffin, 4kV, 50 Torr
0.76nA
4s
I_q

Fig. 3

activity is voltage dependent and is similar to the observation made under transformer oil. However, below 13 kPa at 5 kV and 13 kPa at 7 kV the discharge activity again vanishes. Several authors in the past (*e.g.* Zaky and Hawley 1973), have attributed the increase in discharge activity to the increase in (EHD) motion in oil when stressed under DC; as it was postulated that the enhancement in (EHD) with increase in voltage causes a cavitation process near the high voltage electrode. However, the present results in paraffin are in direct contradiction to that; since the discharge activity disappears below 40 kPa even though the stress level is increased to 7 kV. This is because the current level (see Fig. 2) suddenly drops beyond 40 kPa, as given by equation (2). This sudden reduction in current level at lower pressure does not allow the growth of vaporization to materialize, resulting a decay in the initiation of the vapor cavities thus causing a suppression in the discharge activity.

Table 1. Variation of discharge activity (discharges/100s) with applied voltage (kV) and atmospheric pressure (kPa)

Oil Sample	Voltage (kV)	Pressure (kPa)							
		133	106	80	53	40	26	13	6.5
Fresh	4	3	3	1.5	3	NA	23	> 83	
	5	5	28	7	17	NA	> 83	> 83	
	7	7	5	15	3	NA	> 83	> 83	
Aged	4	13	1	7	1	NA	3	> 83	
	5	7	5	20	1	NA	> 83	> 83	
	7	8.3	5	20	27	NA	> 83	> 83	
Paraffin	4	Nil	Nil	Nil	Nil	Nil	> 66	> 116	> 166
	5	Nil	Nil	Nil	Nil	Nil	> 83	> 7	Nil
	7	Nil	Nil	Nil	Nil	> 83	Nil	Nil	Nil

NA: not available

Conclusion

This experimental work reveals that under sub-atmospheric pressure the DC conduction current remains unaffected down to a certain critical level of pressure and there does not exist any effect of hysteresis. Below this critical level the DC current increases for transformer oil and decreases for liquid paraffin. This opposite behavior can be attributed to the difference in molecular structure of oils. Vaporization is more likely the source of ionization in hydrocarbon oils and therefore plays a dominant role in the mechanism of conduction and discharge activity.

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تيارات التوصيل والنبضات في الزيوت الهيدروكربونية تحت تأثير الضغط المنخفض

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إن الفهم الكامل لتأثير الضغط المنخفض (عن مستوى الضغط الجوي) على تيار التوصيل الثابت في زيوت الهيدروكربون والتي تستخدم كعوازل للمحولات والكابلات الكهربائية هو مهم. فمعظم الباحثين قاموا بدراسة التدهور بين الأقطاب في الفراغ بدون عازلات وبعضهم قاموا بدراسة تأثير الضغط العالي على تيار التوصيل في السوائل وحالياً يحتاج الأمر إلى تجارب منهجية لدراسة تأثير الضغط المنخفض على أداء السوائل العازلة كمحاكاة للأجواء الفضائية وكذلك المناطق الجبلية. وهذه الدراسة مفيدة جداً في مجال علم العازلات الكهربائية والتي لا تخلوا أجهزة الجهد العالي منها.

وهذا البحث يدرس تأثير الضغط المنخفض على تيار التوصيل شبه المستقر وكذلك تيار النبضات في الزيوت الهيدروكربونية. وتم إستخدام مجال كهربي غير منتظم لزيوت غير مستعملة وزيوت تم إستعمالها وكذلك زيت برافين وأمكن خفض الضغط من ١٣٣ ك باسكال إلى ٦,٦ باسكال تم زيادته مرة ثانية إلى ١٣٣ ك باسكال داخل حجرة فراغية. وعند جهد كهربي ثابت، بين البحث أن التيار شبه المستقر يظل ثابتاً بالرغم من إنخفاض الضغط حتى قيمة حرجة والتي يختلف بعدها تصرف الزيوت المختلفة.

فالتيار يزداد بشدة لزيوت المحولات ويقل لزيت البرافين. وقيمة هذا الضغط يزداد مع زيادة الجهد الكهربي. وانخفاض الضغط له تأثير مشابه على تيار النبضات. ويقترح البحث أن التبخر والتركيب الجزئي للزيوت لهما بالغ الأثر عند الضغوط المنخفضة عن الضغط الجوي.